Initiation of Detonation in a Large Tube

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Abstract

One of the important design criteria in the development of Pulse Detonation Engines (PDEs) is to stabilize detonation in a large-diameter tube in the shortest possible distance. The initial shock train emanating from the ignition source plays an important role in transitioning the deflagration wave into a detonation. To sustain such transition in a large-diameter tube, innovative methods and strategies are required. An experimental-numerical investigation is conducted to understand the role of a contoured body suspended within the tube for enhancing detonation transition. A computational fluid dynamics (CFD) code based on flux corrected transport is used for the simulation of the fate of the two-dimensional detonation wave formed from the ignition source and expanded through the gap between the centerbody and the channel walls. It is found that the reflection of transverse waves at the walls and their collision near the leading shock front are critical in sustaining a detonation wave during expansion. The shock-wall and shock-shock interactions are enhanced by the centerbody. Simulations further suggested that the effectiveness of the inserted centerbody strongly depends on its length.

Introduction

Pulse Detonation Engines (PDEs) operate with a higher thermal efficiency than the conventional, constant-pressure combustion engines. PDEs also provide a very high specific impulse thrust at different operating frequencies. They can be designed without the use of any rotating machinery or valves in the flow path. However, the design and operation of the PDEs are complicated by the unsteady, high-speed, pulsed combustion. To reduce the deflagration-to-detonation transition (DDT) time several conceptual procedures have been proposed. The combustible mixture in the main chamber can be ignited using a detonation wave that was generated in a much-smaller, pre-detonation chamber. The primary concern in such approach is the success of the transmission of detonation wave from pre-detonation chamber to main chamber. Previous studies have indicated that the maximum expansion a detonation can successfully go through is of the order of 100%--placing a severe restriction on the detonation-tube diameter [1]. In order to achieve detonation in large-size tubes, alternative techniques need to be developed either with or without using the pre-detonation tubes. This problem of initiating and sustaining detonation in large-diameter tubes is investigated in the present paper using experimental and numerical techniques.

The detailed cellular structures of gaseous detonations have been studied using experimental techniques since 1960's. However, only in the late 1970's Taki and Fujiwara [2] and later Oran et al. [3] were able to numerically simulate the cellular detonation structure for the two-dimensional case. Both the experiments and simulations have identified that the number of cells in a cellular detonation wave is a consequence of the chemistry of the problem, which is characterized by the reaction-zone length scale. The cell size was also found to be independent of the channel width.

An important concern in using cellular detonation wave as a source for burning the reactants comes from the stability of the cellular detonation wave. Experimentally it was found that the stability of the detonation wave increases with tube diameter. For example, a sudden increase in the tube diameter may not quench the detonation if the diameter is greater than thirteen cell widths. As shown by St-Cloud et al. [4] and Moen et al. [5], a finite perturbation may lead to complete destruction of one-cell-width detonations. Therefore, a small but sudden expansion of detonation (or ignition) hotspot may result in a deflagration wave. In the present paper, growth of the ignition spot is controlled via constraining it between the walls of a small tube. Subjecting the resulting localized detonation wave to a weak expansion over the centerbody, the growth of it is controlled.

Experimental Setup:

The photograph of the in-house research PDE used for testing the centerbody concepts is shown in Fig. 1. The engine was equipped with a 5.23-cm-diameter, 71-cm-long ignition tube and a 9.05-cm-diameter, 92.71-cm-long detonator tube. A contoured conical body was mounted inside the detonation tube in such away that its base faces the ignition tube. Hydrogen mixed with air at stoichiometric ratio is detonated at 10 Hz. The detonation tube was instrumented with high-frequency (2MHz) pressure transducers and ion sensors as shown in Fig. 2. The latter

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sensors were used to detect the wave velocity when the detonation front is passing over. Details of the PDE assembly and the incorporated instrumentation are provided in Ref. 6.

Mathematical Model:

The conservation equations for mass, momentum, energy and the two progress variables are solved in Cartesian coordinate system. The gas mixture considered in the numerical investigations is a stoichiometric hydrogen-oxygen fuel diluted with Ar/He by 70%. This mixture is known to generate a well-behaving detonation. The hydrogen-oxygen reactions are represented by the two-step reaction mechanism of Korobeinikov [7]. This model has been successfully applied in the past for addressing various two-dimensional unsteady detonation problems [2,8]. The Chapman-Jouguet (C-J) Mach number of the premixed gas mixture considered is 4.8.

The present simulations used an explicit 2^{nd}-order MacCormack predictor-corrector technique with 4^{th}-order FCT (Flux Corrected Transport) scheme for capturing the shock waves accurately. A 1501x151 grid system is constructed with $\Delta x = \Delta y = L^*/9$. Here, L^* is the induction length--a characteristic distance related to the unburned gas mixture. All the calculations are started by filling the channel with combustible mixture and then by igniting it in a specified region. For the ignition purpose, a circular area of 9-grid-points radius is selected near the closed end of the channel and then replaced the fuel mixture within this region with the combustion products. In constant-width channels, a stably propagating multi-dimensional detonation wave establishes as the combustion products push the flame front.

Results and Discussion

Experiments were conducted by suspending a conical centerbody at 2.79 cm downstream of the reference point in the detonation tube (Fig. 2). Ignition was provided with spark plugs placed in the ignition tube. A weak deflagration combustion wave was established in the ignition tube and was expanded in the detonation tube. Typically, such expansion further weakens the combustion wave. In the absence of the centerbody, the responses from the pressure transducers 4 and 7 as the combustion wave passes over them are shown in Fig. 3. The relative pressure increased only to ~ 0.6 at the leading edge of the combustion wave. The measured wave speeds are ~ 650 m/s.

Placement of centerbody in the detonation tube helped the deflagration combustion wave to transition into a detonation wave. The pressure waves obtained from sensors 4 and 7 are shown in Fig. 4(a) and the voltages recorded by the ion sensors 8 and 10 are shown in Fig. 4(b). The measurement of wave speed varies from 1800 to 2200 m/s, depending on the sensor location. This wave speed compares favorably with the C-J velocity of 1966 m/s for the stoichiometric H_2/Air mixture at 1 atm pressure.

To verify the DDT process assisted by the centerbody, simulations were made using the two-dimensional code described earlier. Calculations were made initially for a channel width of $9L^*$ without using a centerbody. A stably propagating detonation wave having two transverse waves was established after ~1000 time steps starting from a single ignition spot. The interaction between the transverse and detonation waves results in a triple-shock structure and thereby a cellular detonation front. As the detonation propagates, these transverse waves travel toward the walls and reflect back when they interact with the walls. The structure of the detonation front propagating in the $9L^*$ channel is shown in Fig. 5 at three instants. The iso-pressure plots shown in Figs. 5(a), 5(b), and 5(c) visualize the motion of the two triple shock structures between the lower and upper walls. The wave velocities obtained at upper and lower walls and at the mid section showed that the reflection of a triple shock from the wall and the interaction between two triple shocks result in enhanced combustion (increased propagation velocity) locally. However, the average non-dimensional propagation velocity was 4.96, which is close to the Chapman-Jouguet (C-J) velocity for the mixture considered.

Calculations were then repeated for a channel having a width of $18L^*$ and without placing a centerbody. A single ignition spot failed to yield a stably propagating detonation wave. Placing an additional ignition spot did not help much in detonating the gas all across the channel. The ignition spots are also partially enclosed in small chambers to enhance shock reflections off the walls. The failure of detonation initiation for this case is shown in Fig. 6(a). Here, the bottom image shows the deflagration wave that reached the channel exit 58 μs after the ignition and the top image shows the changes in pressure at the upper wall with time. However, detonations were successfully initiated when the ignition energy was doubled as shown in Fig. 6(b). This demonstrates that a stable detonation can be obtained, even though difficult, in the $18L^*$-wide channel.

The possibility of achieving a stable detonation from the normal ignition energies is investigated by placing various centerbodies in the $18L^*$-wide channel. Due to the orthogonal grid system used in the code, each centerbody is constructed with different-size blocks as shown in Figs. 7-9. Detonation could not be established with the $32L^*$-long centerbody. A comparison of detonation developments shown in Figs. 6(a) and 7 suggests that the initial shock waves established from the ignition source have dissipated more rapidly in the presence of the centerbody. However, when the centerbody length was increased to $39L^*$, a stable detonation was established (Fig. 8). Interestingly, detonation could not be sustained when the centerbody length was further increased to $46L^*$. The three calculations with different centerbody lengths suggest that 1) placing a centerbody can help establishing detonation in a large-diameter tubes and 2) the effectiveness of the centerbody depends on its length, probably in relationship with the cell width. The variation in wall pressure at $100L^*$ downstream of the back plate are shown in Fig. 10 for different

centerbody cases. It clearly shows the establishment of detonation in the case of the medium-length ($39L^*$) centerbody and failure in the other cases.

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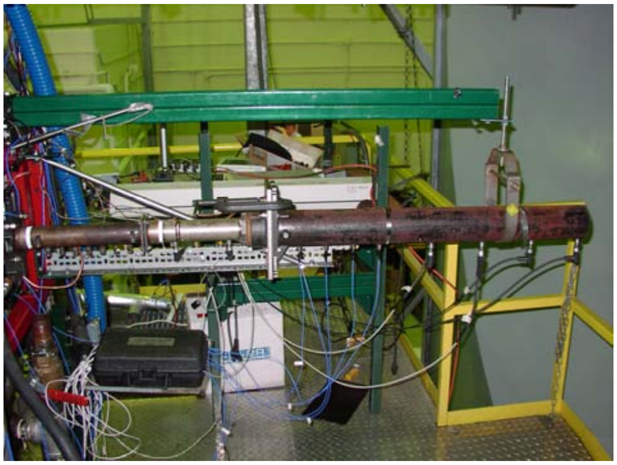


Fig. 1. Experimental facility used for the studies of fundamental concepts in detonation initiation and propagation.

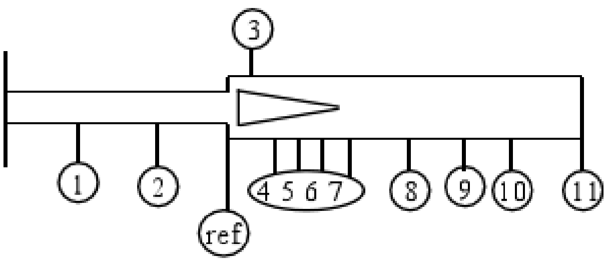


Fig. 2. Schematic diagram of the detonation tube assembly and locations of centerbody and sensors. 3-7 are pressure transducers and 1,2, 8-11 are ion detectors.

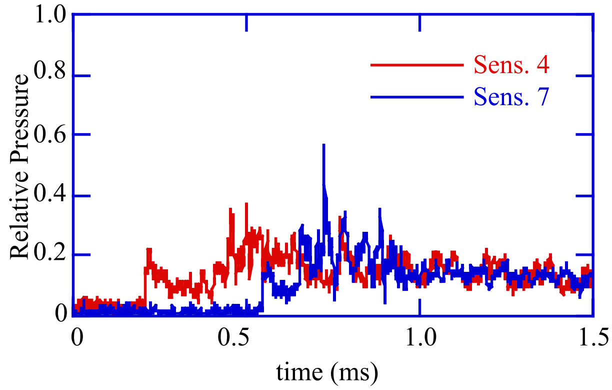


Fig. 3. Deflagration wave propagation detected by pressure transducers 4 and 5 in the absence of centerbody.

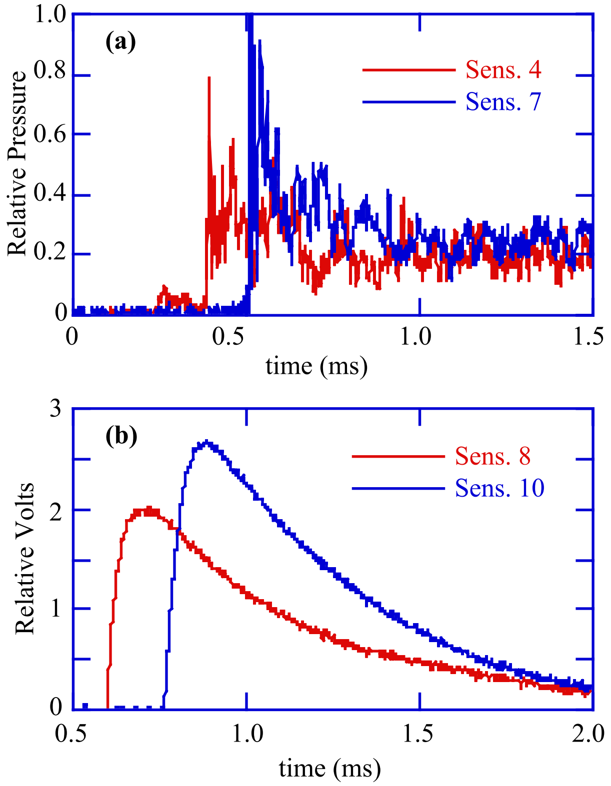


Fig. 4. Responses of (a) pressure transducers 4 and 7 and (b) ion detectors 8 and 10 during a successful detonation initiation achieved by placing centerbody.

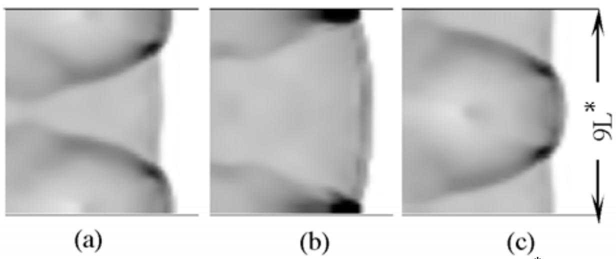
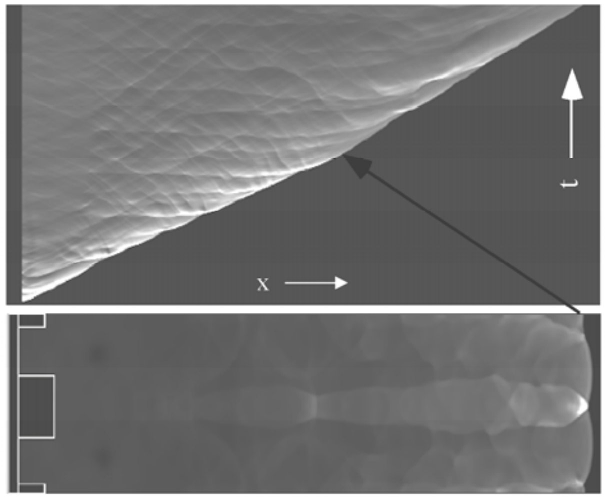
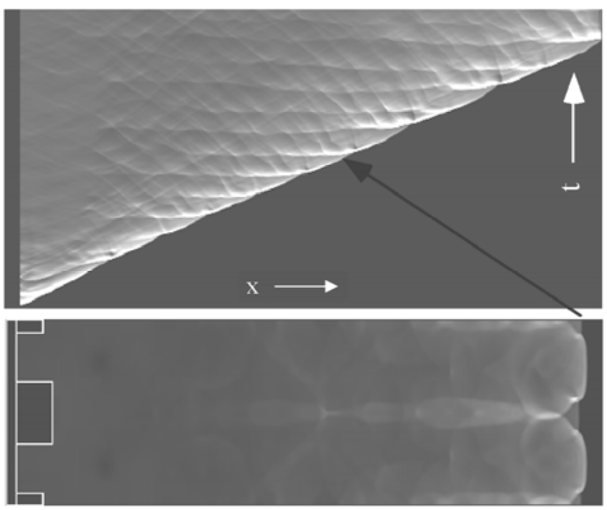


Fig. 5. Stably propagating detonation wave in a $9L^*$ channel at (a) t_0 μs, (b) t_0+1.6 μs, and (c) t_0+3.2 μs.



(a)



(b)

Fig. 6. Detonation propagation in 18L* wide channel with (a) specified and (b) 100% more ignition energies.

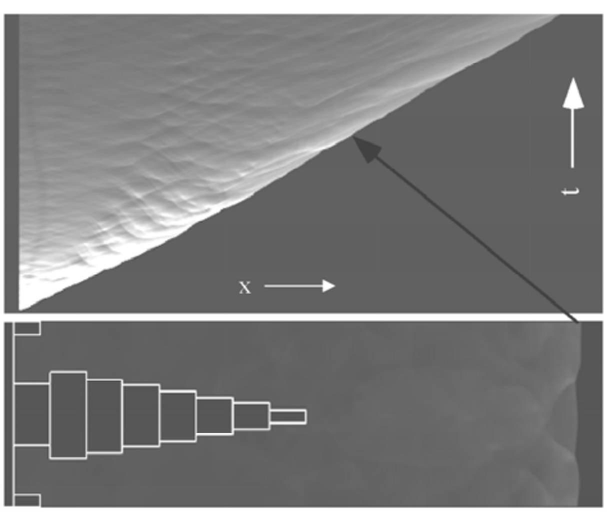


Fig. 7. Effect of placing 32L* long centerbody. Upper image shows wall pressure at different times.

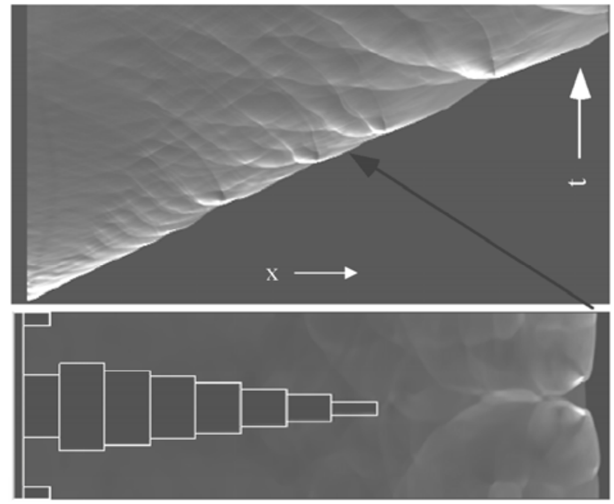


Fig. 8. Effect of placing 39L* long centerbody. Upper image shows wall pressure at different times.

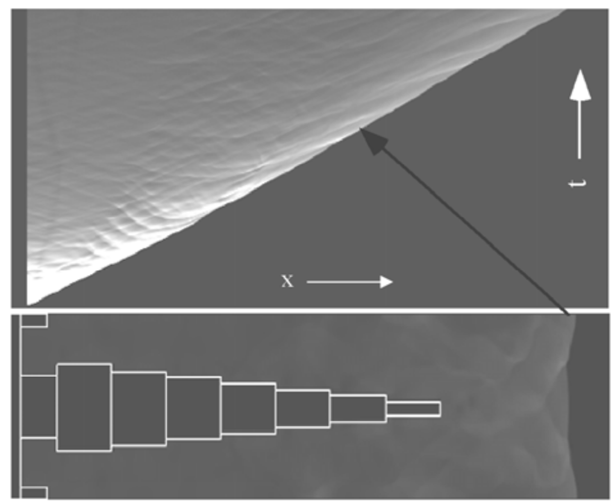


Fig. 9. Effect of placing 46L* long centerbody. Upper image shows wall pressure at different times.

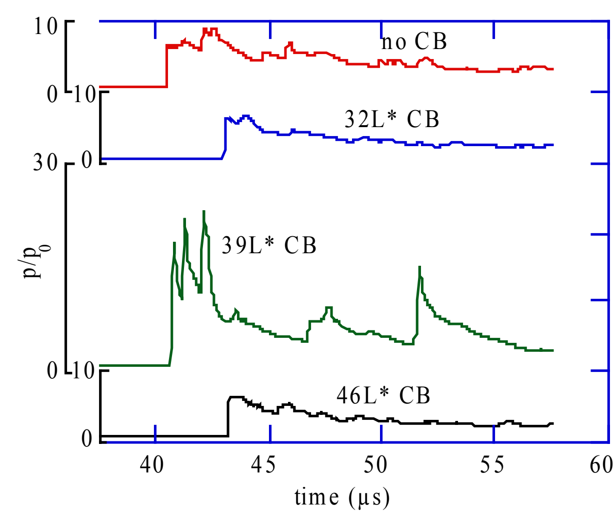


Fig. 10. Variation of wall pressure at a location 100L* downstream of back plate.